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Geoscience Research
GSI
Suirbhéireacht Gheolaíochta Éireann
Geological Survey of Ireland

Geological Survey of Ireland Research Programme
- Short Call 2015, Final Report -

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Organisation name	National University of Ireland, Galway (NUIG)		
Organisation type:	☒HEI	☐Public Sector (other)	☐Private Sector
Department/section	Earth and Ocean Sciences		

Project Title	Linking sedimentary architecture and sediment sources in the NW Carboniferous Basin
Contract No.	2015-sc-029

INFOMAR
Integrated Mapping for the Sustainable Development of Ireland's Marine Resource

Tellus
Understanding Underground

Marine Institute
Foras na Mara

2. Project information:

Title of project	Linking sedimentary architecture and sediment sources in the NW Carboniferous Basin.
Did you make any formal amendment to the project workplan / budget?	☐ yes ☒ no If yes, please specify:

Project Report (*max 1500 words, excluding figures and headings*):

(i) Objectives and scientific/engineering targets beyond the state of the art

The aim of this project was to investigate the clastic sedimentary infill of the NW Carboniferous Basin (NWCB), onshore northwest Ireland. The basin is a prime target for large-scale structural and basin evolution studies taking place within iCRAG (Irish Centre for Research in Applied Geosciences) and is an excellent test bed for examining the architecture and evolution of a shallow marine – fluvial-deltaic sedimentary system as preserved in the Mullaghmore Sandstone Formation (MSFm; Figure 1).

Specifically, this research aimed to determine links between the depositional architecture of the NWCB/MSFm and sediment sourcing by utilising a novel, multi-proxy provenance approach. The

application of multiple provenance tools (e.g. major and trace element data, petrography, U-Pb zircon geochronology and Pb-in-K-feldspar analysis) has allowed the fluctuations in sedimentary sand supply to be characterised. This in turn allows for the reconstruction of the palaeogeography of both the basin and the surrounding hinterland during this part of the Carboniferous (Viséan Stage, c. 346–330 Ma) and illustrates how the sedimentary system and supply evolved through this time interval. In general, sedimentary structures in the MSFm suggest derivation from the north-north west, although the precise source for these sediments has, to-date, remained unclear (Graham, 1996).

By better understanding the evolution of the siliciclastic fill in this basin, the distribution and character of key stratigraphic intervals can be better constrained, with consequent implications for similar depositional systems which are prospective for economic resources in other parts of the world (e.g. Gulf of Mexico).

The main questions of this research were –

- Where are the sandstones in the NWCB sequence coming from and do the sedimentary sources change through time?
- What are the implications for Carboniferous palaeogeography and what are the scales and routeways taken by the sediment delivery system?
- What are the controls on the supply of coarse clastic material and do these have implications for basins elsewhere?

This project has built on Ireland's growing expertise in the area of sedimentary provenance research and was carried out within an emerging research group based at NUI Galway. This group works closely and in collaboration with researchers in the "*Sediment Tracking*" targeted project within the Hydrocarbons spoke of iCRAG (Irish Centre for Research in Applied Geosciences) which includes researchers in TCD,

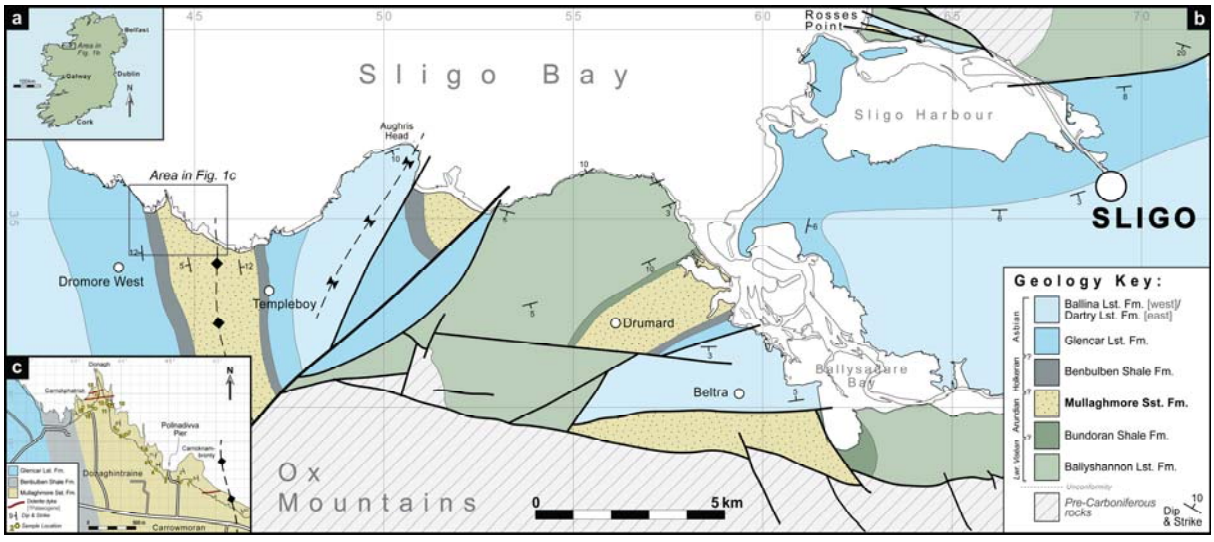

Fig. 1: (a) General location of study area. (b) Regional-scale geological map of the Sligo Bay area, showing distribution of Carboniferous strata, including the Mullaghmore Sandstone Formation. The ages of the various Viséan units are (tentatively) indicated in the key. Location of more detailed map in (c) also shown. (c) Detailed geological map of logged area, with sample locations in the MSF highlighted. Geological maps in (b) and (c) adapted from MacDermot et al. (1996) [Geological Survey of Ireland 1:100K Sheet 7 (Sligo-Leitrim)], with modifications in (c) based on direct field observations of the authors.

UCD and UCC. Co-PI, Dr John Murray (NUIG) provided expertise in Carboniferous sedimentology and stratigraphy. Researchers from TCD (Dr David Chew and Prof John Graham) were also consulted for their expertise in U-Pb zircon geochronology and Carboniferous sedimentology of the NWCB respectively.

Despite some delays in securing staff (see section ii below) the above objectives were met and the outcomes, including specific and generic implications of the results, are detailed in section iii. It was not possible, as initially hoped, to integrate these data with Tellus, as ultimately the sampling and sedimentological investigations were restricted and focussed on a very small area of coast. There is potential to utilise Tellus datasets if, as planned, the project is expanded across the broader NWCB.

(ii) Implementation (including reference to timelines, milestones, management)

The research comprised both a field and laboratory component. A research assistant, Bebhinn Anders, was employed for a period of 4 months, beginning 18th May 2016 – a delay of several months from the original proposed start date. Ms Anders carried out the detailed field work, the subsequent lab analysis and the synthesis of the results.

In summary the work programme entailed:

- Sedimentary logging and facies analysis of the entire Mullaghmore Sandstone Fm. exposed along Carrowmoran Shore, Sligo (Figure 2).
- Careful sampling to obtain the full variation of sandstones and facies packages present.
- Processing of 16 samples, including crushing, milling and thin section preparation. The processing had to be carried out externally due to lack of suitable facilities in NUIG.
- Chemical analysis (major and trace element analysis) of all 16 samples. The geochemical data was plotted in order to illustrate variations in composition and/or sand sourcing.
- Optical microscopy and petrographic analysis of 16 thin section sedimentary samples. Those with most abundant and good-quality K-feldspar were selected for Pb-K-feldspar analysis.
- 16 samples were sieved, a subset of which was processed for heavy mineral separation, and the extraction of zircons. Approximately 1000 zircon grains were picked and mounted. 5 samples in total were selected for U-Pb zircon analysis, carried out in TCD in collaboration with Dr David Chew and Dr Chris Mark.
- Scanning electron microscopy imaging of thin section samples. A subset of 3 samples were selected for Pb-in-K-feldspar analysis. This work was carried out in the National Centre for Isotope Geochemistry at UCD.
- Synthesis of all datasets and production of poster presentation for Geosciences 2016 (a PDF of the poster is attached at the end of this report).

(iii) Outputs (please use bullet points)

- The 80 metres of logged section through the Mullaghmore Sandstone Formation displays the characteristics of a **prograding, wave-dominated, delta,** with a typical coarsening upwards signature. Palaeoflow recorded in the field indicates derivation from the NW (Figure 2).

- The logged section can be subdivided into **6 distinct facies packages**: A) Prodelta mudstones;

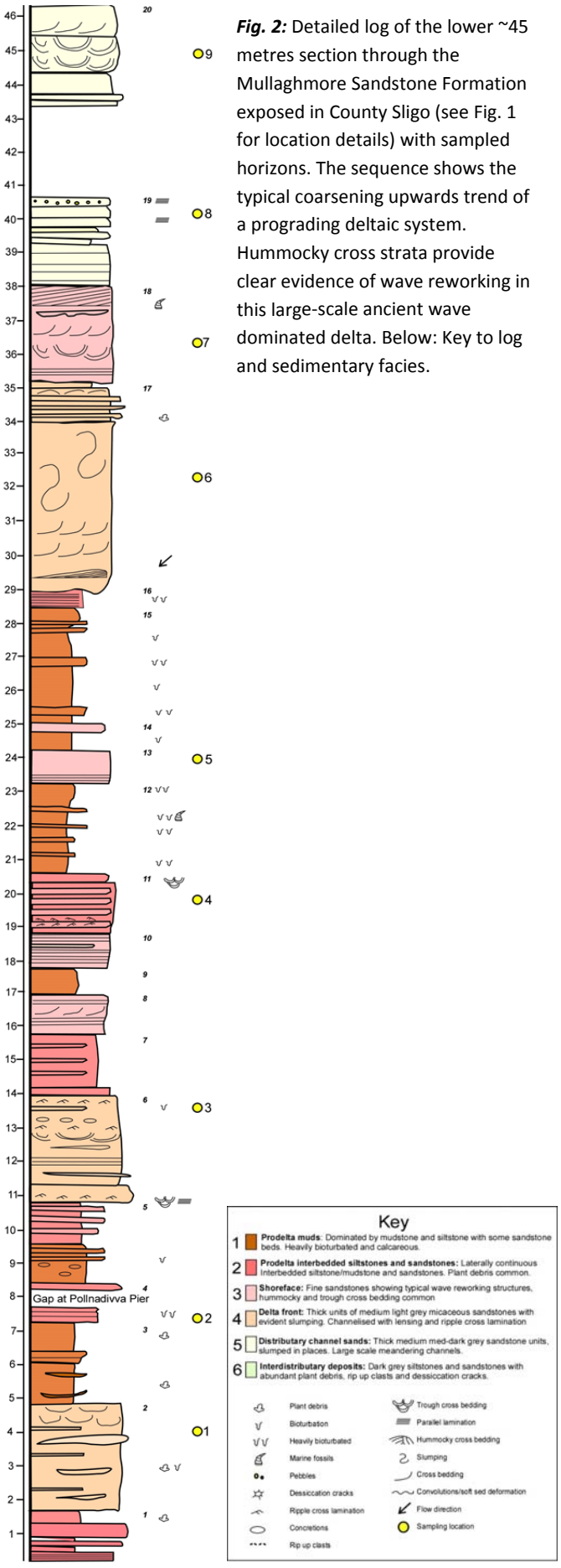

Fig. 2: Detailed log of the lower ~45 metres section through the Mullaghmore Sandstone Formation exposed in County Sligo (see Fig. 1 for location details) with sampled horizons. The sequence shows the typical coarsening upwards trend of a prograding deltaic system. Hummocky cross strata provide clear evidence of wave reworking in this large-scale ancient wave dominated delta. Below: Key to log and sedimentary facies.

B) Prodelta fine sandstones and siltstones; C) Shoreface; D) Delta front; E) Distributary channel sandstones; F) Interdistributary deposits

- **Rare earth element data** illustrates a small variation in sandstone composition which could be linked to differing sediment supply

- **U-Pb zircon geochronological** data indicates supply of zircon from three distinct source regions likely corresponding to 1) Archaean - Palaeoproterozoic crust (such as the Lewisian Complex of NW Scotland or the Nagsuggtoqidian of eastern Greenland; 2) “Laurentian” affinity crust (i.e. dominantly Mesoproterozoic crust which has been affected by the Grenville Orogeny, such as the Annagh Gneiss Complex (AGC) of NW Mayo); and 3) Caledonian-aged detritus (400-500Ma).

- The U-Pb zircon data suggest that **supply of ‘Laurentian’ affinity material appears to dominate,** while Caledonian-aged detritus is always sub-ordinate implying that derivation from a local Caledonian source, such as the Donegal Granite, was subdued or did not contain significant zircon.

- **Pb-in-K-feldspar analysis** shows several grain populations which seem to correspond with 1) Archaean - Palaeoproterozoic crust with strong similarity to offshore Lewisian Complex equivalents (Stanton Banks); and 2) “Laurentian” affinity crust (rocks that have experienced the Grenville Orogeny) such as the AGC or an offshore equivalent. Similar to the U-Pb zircon data, there are very few grains which could have come from Caledonian granites such as those in Donegal

- These provenance data are consistent with **supply from the north west**, with a mix of more proximal terranes, such as the AGC (onshore) and the Erris Ridge (offshore) and more

distal sources (eastern Greenland, the Hebridean Platform), supplying the bulk of the detritus. Significant sourcing from Caledonian sources such as the Donegal Granite is ruled out.

- **The supply to the basin appears to fluctuate through time** with some correspondence between facies packages and the provenance signal. For example, distributary channel sands (Sample 9) appear to be dominated by 1.7Ga zircons, while shoreface sands (Sample 5) have a far more diverse signature (Figure 3). This suggest "point sourcing" of sand supply producing a "less mixed" signal in the case of channelized sands, with a varied distribution for those sands "mixing" on a shelf and incorporating supply from multiple "point sources".

- These results have important implications for Carboniferous palaeogeography (note the important role played by offshore basement highs to the NW of Ireland), but also as to how provenance tools should be applied to sedimentary systems. The study highlights the importance of incorporating detailed sedimentological and facies analysis into provenance studies.

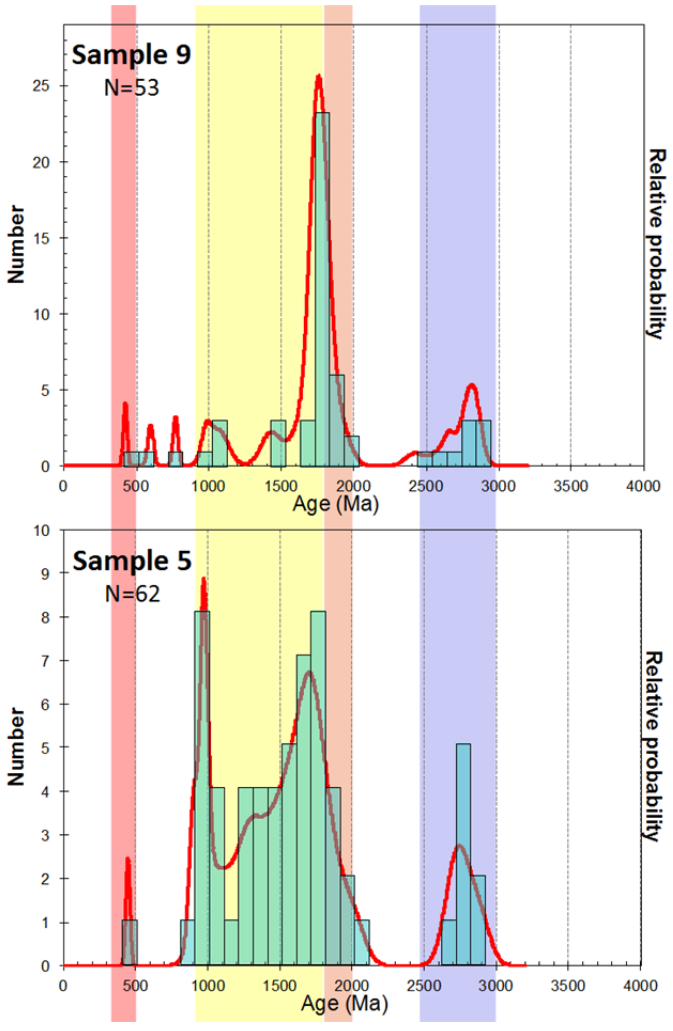

Fig. 3: Histogram and probability density curves for U-Pb zircon ages from samples 5 (shoreface) and 9 (distributary channel) in the logged section through the MSFm (Figure 2). Only concordant grains were plotted to minimise any errors in determination of provenance populations; however, there is no difference in the overall population signal if all grains (concordant and disconcordant) are plotted. Broad age ranges for Caledonian (Red), "Laurentian" affinity crust (yellow) and Lewisian Complex/ Nagsuggtoqidian (East Greenland) basement (younger component in brown, older in blue) superimposed for comparative purposes. Note the unimodal appearance of sample 9 compared to the more "mixed" signature in sample 5.

Impact/value of the project (M*ax 500 words*):

This pilot study has been an effective demonstration of some important concepts that are often overlooked in provenance analysis or "source to sink" modelling – namely that the variation in sand supply with sedimentary facies must be assessed in sedimentary systems. Facies which are more likely to be "*point sourced*" (i.e. fluvial channels) seem to show a more unimodal provenance signature that those which are "*mixed*" (i.e. shelf sands). This work may have important and generic implications for the use of provenance analysis when applied to the reconstruction of ancient drainage patterns, basin evolution studies and, especially, if they are used as a correlation tool. Contemporaneous sandstones deposited even within a small basinal area may not necessarily yield the same provenance signature.

The work has already been presented at Geoscience 2016 and Atlantic Ireland 2016 and will be presented again at the British Sedimentological Research Group, AGM2016 at the University of Cambridge in late December. It is envisage that results and synthesis of this project will be published in a peer review journal within the next 6 months (with due and appropriate acknowledgement to the GSI) and that the results will form the basis for an application for further funding to expand this into PhD project for the RA, Bebhinn Anders, who is very eager to continue this line of research. A proposal for further funding is in hand and it is envisaged that an application will be submitted to the Irish Research Council and the NUIG College Scholarship Scheme in early 2017.

Appendix 1 – Publications & Presentations:

[Conference Publication] Anders, B.; Tyrrell, S.; Murray, J.; Graham, J.R.; Mark, C; Chew, D. (2016) Linking sedimentary facies and sediment sources in the NW Carboniferous Basin. *Atlantic Ireland 2016*, Dublin, 1st-2nd November.

[Conference Publication] Anders, B.; Tyrrell, S.; Murray, J.; Graham, J.R.; Mark, C; Chew, D. (2016) Fluctuating sand supply to a prograding delta: provenance of the Mullaghmore Sandstone Formation, NW Carboniferous Basin, Ireland. *British Sedimentological Research Group, AGM2016*, University of Cambridge, UK, 18th-20th December.

Appendix 2 – Any additional information not included above:

Linking Sedimentary Architecture & Sediment Sources in the NW Carboniferous Basin

Anders, B.[1*], **Tyrrell, S.**[1,2], **Murray, J.**[1,2], **Graham, J.R.**[3], **Marks, C.**[2,3] & **Chew, D.**[2,3]

1:Earth and Ocean Sciences, School of Natural Sciences, National University of Ireland, Galway, Ireland; **2:** Irish Centre for Research in Applied Geosciences (iCRAG); **3:**Department of Geology, Trinity College Dublin, Dublin 2, Ireland.

***Corresponding author: bebhinn.anders@nuigalway.ie**

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Introduction

This project aims to develop a clearer understanding of the nature, evolution and architecture of the sedimentological fill of the **North West Carboniferous Basin** [**NWCB**] in northwest Ireland. The NWCB occupies an area of c.600km^2 and is spread across counties Cavan, Donegal, Fermanagh, Leitrim, Mayo, Monaghan, Roscommon and Sligo. It has been the focus for unconventional hydrocarbon exploration in Ireland and this pilot project is thus of crucial importance for assessing its hydrocarbon potential.

The initial focus is on the **Mullaghmore Sandstone Formation** [**MSF**] which is Viséan (Carboniferous; Mississippian) in age. An almost complete lithostratigraphic section through the MSF was examined on the north Sligo coast between Carricknagrauv and Carrickphatrick (**Figs. 1** & **2**).

This research specifically aims to constrain links between sediment supply and the depositional architecture of this ancient fluvial system through high resolution sedimentological and provenance analysis. A multi-proxy approach will be employerd to help reconstruct the palaeogeography of the NWCB and its hinterland, and to shed light on the evolution of the sedimentary system through time.

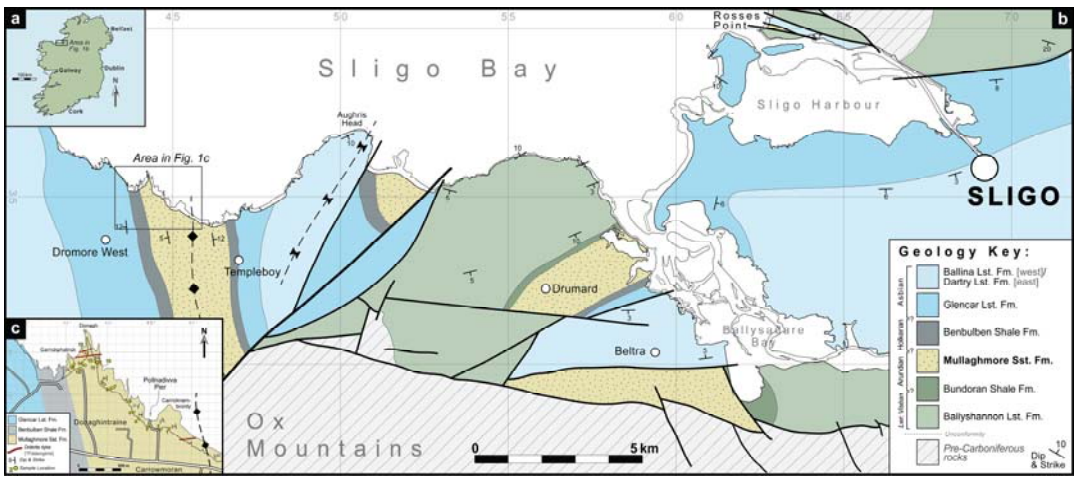


Fig. 1 – (Above): ***(a)*** *General location of study area.* ***(b)*** *Regional-scale geological map of the Sligo Bay area, showing distribution of Carboniferous strata, including the Mullaghmore Sandstone Formation. The ages of the various Viséan units are (tentatively) indicated in the key. Location of more detailed map in (c) also shown.* ***(c)*** *Detailed geological map of logged area, with sample locations in the MSF highlighted.*

Geological maps in (b) and (c) adapted from MacDermot et al. (1996) [Geological Survey of Ireland 1:100K Sheet 7 (Sligo-Leitrim)], with modifications in (c) based on direct field observations of the authors.

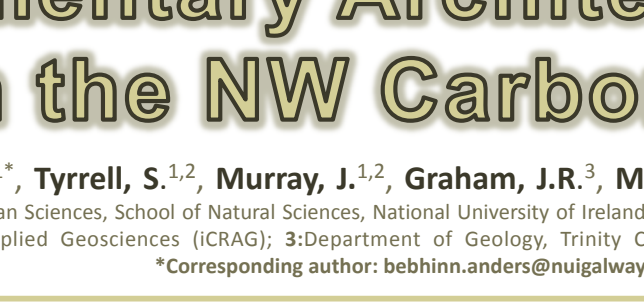


Fig. 3 – (Left): *Whole-rock data REE plots of six selected samples from the MSF (from the 16 samples recovered in total). Samples not depicted on this diagram follow the same behaviour as Samples 1, 5, 9 and 15, with LREE depleted and HREE enriched. Sample 12 shows a different behaviour (LREE enriched and HREE depleted) suggesting a different provenance for this sample. Like Sample 1 it is also missing the typical Europium anomaly.*

Methods

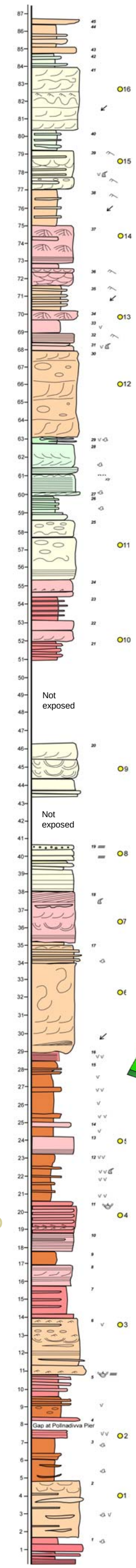
A detailed sedimentological log through the MSF was recorded in the field in County Sligo (**Fig. 2**).

Distinct facies packages were identified, displaying fluctuating sand supply to the fluvial/deltaic system.

A **multi proxy provenance approach** utilising:

- Optical microscopy
- Scanning electron microscopy
- Major & trace element whole rock data
- U-Pb zircon &
- Pb-in-K-feldspar

has been adopted, maximising potential insight into fluctuating sand supply.



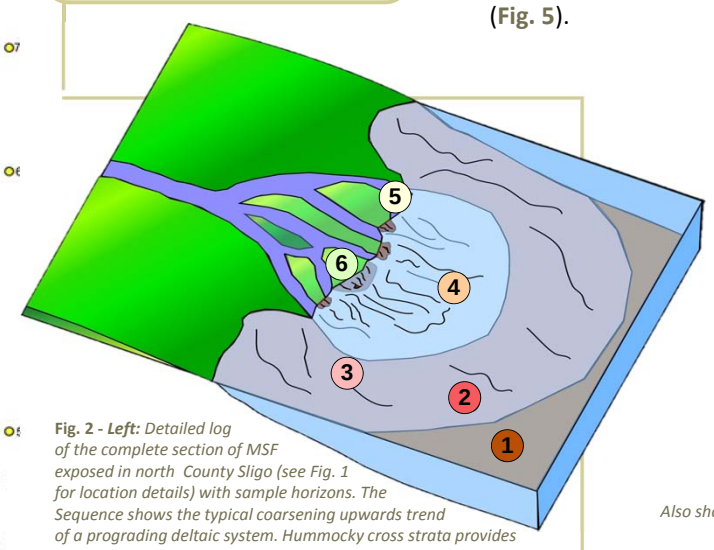


Fig. 2 - *Left:* *Detailed log of the complete section of MSF exposed in north County Sligo (see Fig. 1 for location details) with sample horizons. The Sequence shows the typical coarsening upwards trend of a prograding deltaic system. Hummocky cross strata provides clear evidence of wave reworking in this large-scale ancient wave dominated delta.* ***Below:*** *Key to log and sedimentary facies.* ***Above:*** *Reconstruction of a delta showing the location of each facies package [1-6 described in key below].*

Key

1. **Prodelta muds**: Dominated by mudstone and siltstone with some sandstone beds. Heavily bioturbated and calcareous.
2. **Prodelta interbedded siltstones and sandstones:** Laterally continuous interbedded siltstone/mudstone and sandstones. Plant debris common.
3. **Shoreface:** Fine sandstones showing typical wave reworking structures, hummocky and trough cross bedding common
4. **Delta front:** Thick units of medium light grey micaceous sandstones with evident slumping. Channelised with lensing and ripple cross lamination
5. **Distributary channel sands:** Thick medium med-dark grey sandstone units, slumped in places. Large scale meandering channels.
6. **Interdistributary deposits:** Dark grey siltstones and sandstones with abundant plant debris, rip up clasts and dessiccation cracks.

Plant debris; Bioturbation; Heavily bioturbated; Marine fossils; Pebbles; Dessiccation cracks; Ripple cross lamination; Concretions; Rip up clasts; Trough cross bedding; Parallel lamination; Hummocky cross bedding; Slumping; Cross bedding; Convolutions/soft sed deformation; Flow direction; Sampling location

Results

- **Sedimentary structures** observed in the field in the Mullaghmore Sandstone Formation suggest a palaeoflow from NE to SW (**Fig. 2**).
- **REE data** for the MSF suggest various sources of sand supply to this large fluvial/deltaic system, as suggested by the differing REE patterns (**Fig. 3**).
- **U-Pb Zircon analysis** (**Fig. 4**) demonstrates that the majority of the grains in the MSF are dominated by zircons with an age range of 1–1.7 Ma, which is a typical 'Laurentian' signal. A minor amount of grains derive from the Caledonian, with probable sources from the Donegal Granite. The third set of zircons date to the Palaeoproterozoic to Archaean, with a probable source from Greenland and/or NW Scotland.
- **Pb-in-K-feldspar analysis** is currently underway; however, previous data for the MSF from a location further east in County Sligo suggests sediment sources from NW Scotland or Greenland, and also the Donegal Granite (**Fig. 5**).

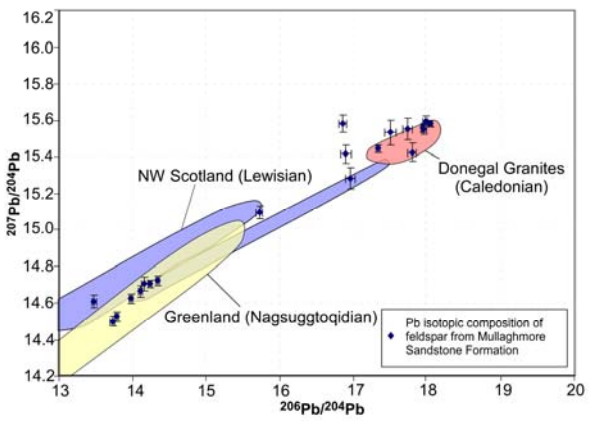


Fig. 5 – *Above:* *$^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ for K-feldspars from the Mullaghmore Sandstone Formation from a previous study. Also shown are ranges of Pb isotopic composition of detrital K-feldspar from NW Scotland (Lewisian), Greenland (Nagsuggtoquidian) and the Donegal Granite (Caledonian).*

Preliminary Conclusions

The Mullaghmore Sandstone Formation displays the characteristics of a delta, with palaeoflow indicating progradation from the NE. Preliminary provenance analysis suggests supply from three distinct source areas:

1) Archaean - Palaeoproterozoic crust (e.g. Lewisian of NW Scotland or Nagsuggtoqidian of eastern Greenland)
2) 'Laurentian' affinity crust *and*
3) Caledonian-aged rocks (e.g. the Donegal Granite)

The supply of 'Laurentian' affinity material appears to dominate, while Caledonian-aged detritus is always sub-ordinate.

Derivation from these source areas is consistent with the observed palaeoflow direction in the deltaic system. The provenance results also hint at fluctuations in supply during deposition of the system – this will be further investigated with the application of an additional provenance tool – Pb isotopes in K-feldspar.

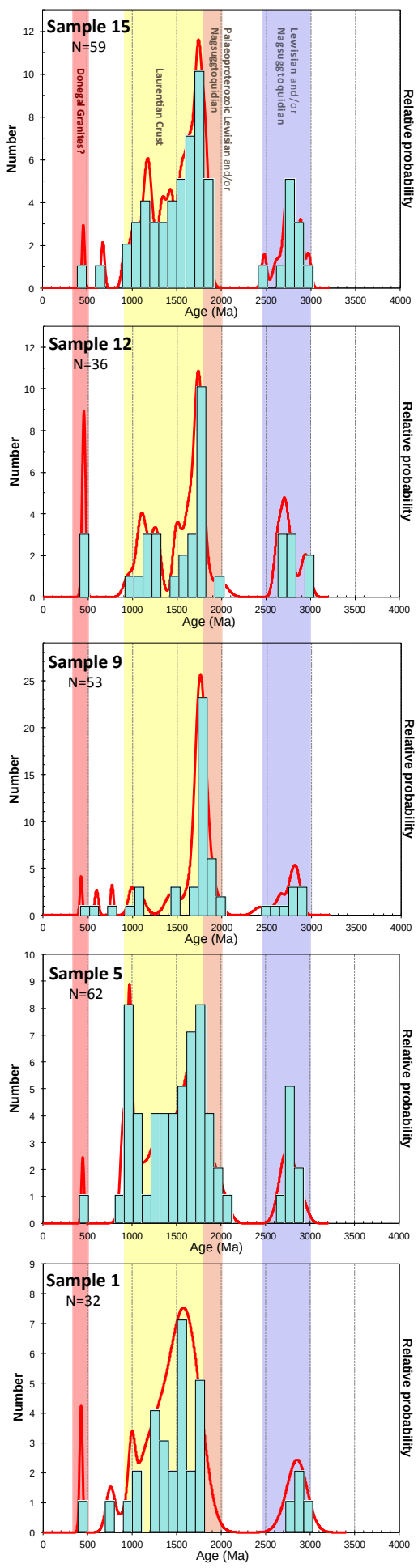


Fig. 4 – *Above**: Histogram and probability density curves for U-Pb zircon ages from the 5 samples in the logged section through the MSF. Only concordant grains were plotted to minimise any errors in determination of provenance populations; however, there is no difference in the overall population signal if all grains (concordant and disconcordant) are plotted. Broad age ranges for Caledonian, "Laurentian" affinity crust and Lewisian Complex/ Nagsuggtoqidian basement superimposed for comparitive purposes.*